NOTES ON THE KELVIN BRIDGE

NOTE BOOK 4

1929

LEEDS & NORTHRUP COMPANY

ELECTRICAL MEASURING INSTRUMENTS

PHILADELPHIA

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CONTENTS

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LEEDS & NORTHRUP COMPANY
ELECTRICAL MEASURING INSTRUMENTS
4901 STENTON AVE. - - PHILADELPHIA, PA., U. S. A.

PURPOSE OF THE KELVIN BRIDGE

For accurate measurement of low electrical resistance the most convenient method is that of the Kelvin bridge, sometimes called the Thomson bridge*. This method has been in use for many years in research and standardizing laboratories for such purposes as checking and comparing low resistance standards and for measuring the resistance of current carrying shunts. In recent years, as its merits have become more generally recognized, it has found increasing use for determining the electrical conductivity and the temperature coefficient of wire and rod, and for measuring the resistance of the windings of large generators, motors and transformers, and other electrical conductors of low resistance. Application of the method is also made in measuring and recording the temperature of low resistance windings.

The chief purpose of this note book is to provide information that will be of assistance in the operation of a Kelvin bridge. The fundamental principles of the Kelvin bridge method for measuring low resistance are first explained, and then follows a discussion of several types of Kelvin bridge suitable for different applications of the method. These include a Standard Kelvin Bridge for very precise measurements, a Self-Contained Kelvin Bridge for general use, two Portable Kelvin Bridges, and a Students' Kelvin Bridge particularly adapted to instruction in the theory and use of the method. A Kelvin Bridge Temperature Recorder for rotating field windings is also described.

Requirements for Low Resistance Measurement:

In measuring low resistance with a Kelvin bridge the procedure is similar in some respects to that in measuring higher resistance with a Wheatstone bridge. The unknown resistance is connected in one branch of a bridge circuit, and a calibrated resistance in another branch is adjusted until a galvanometer shows that the circuit is electrically balanced. The relation of the unknown resistance to the standard resistance is then indicated by the relation of resistances in two other branches of the circuit called the ratio arms. The significant difference between the Kelvin bridge circuit and the Wheatstone bridge circuit is in the effect produced by the resistance of leads and contacts in connections between the bridge and the unknown resistance. In the ordinary Wheatstone bridge circuit the resistance of leads and contacts is part of the total resistance measured, and may cause a very considerable error in the measurement of resistances of less than 0.1 ohm. In the Kelvin bridge circuit the effect is rendered relatively insignificant by putting the leads and contacts in series with high resistances in the ratio arms. To do this requires the use of a double ratio, and of distinct current and potential

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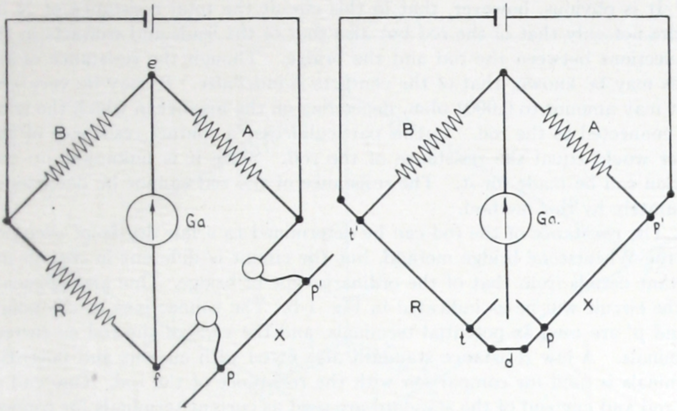
*This method for measuring resistance was first described by Sir William Thomson—later Lord Kelvin—in 1862.

PURPOSE OF THE KELVIN BRIDGE (Continued)



Figs. 1a and 1b

terminals for both the standard and the unknown resistance. The resistance measured is that between the potential terminals. The essential features of the Kelvin bridge circuit are demonstrated in the following discussion by showing the elements of error in the measurement of low resistance with a Wheatstone bridge, and the manner in which the limitations of this circuit are overcome in the Kelvin bridge.

For example, it may be necessary to measure the resistance between two points p and p′ a foot apart on a ⅜-inch copper rod. If an ordinary type of Wheatstone bridge is used, leads attached to the two points on the rod will be clamped to binding posts in one arm of the bridge, as indicated in Fig. 1-a. This shows a conventional diagram of the Wheatstone bridge circuit, in which the resistance to be measured is represented by X, and R is the rheostat arm in which resistance can be adjusted to balance the bridge circuit. The amount of resistance required in R for balance against X depends on the ratio of the resistances in A and B, the ratio arms of the bridge.

The bridge is balanced by an adjustment of R until the potential at f is the same as that at e, as indicated by zero deflection of the galvanometer. The resistances in the four branches of the circuit are then in the relation

$$\frac{X}{R}=\frac{A}{B}$$

so that the unknown resistance should be determined from the formula

$$X=\frac{A}{B}R$$

PURPOSE OF THE KELVIN BRIDGE (Continued)

It is obvious, however, that in this circuit the total resistance of X includes not only that of the rod but also that of the leads and contacts in the connections between the rod and the bridge. Though the resistance of the leads may be known, that of the contacts is indefinite. It may be very low, or it may amount to 0.0001 ohm, depending on the manner in which the wires are connected to the rod. In this particular case a contact resistance of this order would equal the resistance of the rod. Since it is unknown, no correction can be made for it. The resistance of the rod cannot be determined accurately by this method.

The resistance of the rod can be determined to a fair degree of accuracy by the Wheatstone bridge method, but the circuit is different in certain important details from that of the ordinary type of bridge. One arrangement* of the circuit will be as indicated in Fig. 1-b. The connections to the points p and p' are used as potential terminals, and the ends of the rod as current terminals. A low resistance standard also fitted with current and potential terminals is used for comparison with the resistance of the rod. One end of the rod and one end of the standard are used as current terminals for connection to the battery. The current terminals at the opposite ends of rod and standard are connected by a low resistance yoke d. The resistance of A is fixed, but that of B is adjustable. One galvanometer terminal is connected to the junction between A and B, and the other can be connected alternately to p and t, so that two separate measurements can be made.

For one measurement the connection is made to t, and B is adjusted until the bridge is balanced. If B_1 denotes the resistance required for balance, and d the total resistance between t and p, including that of the yoke and that of the two current terminals joined to it, the relation of the resistances in the four arms will be

$$\frac{A}{B_1} = \frac{X+d}{R}$$

For the other measurement the galvanometer terminal is connected to p, and B is again adjusted. If the resistance required for balance in this case is B_2, the relation of the four resistances will be

$$\frac{A}{B_2} = \frac{X}{R+d}$$

The two equations can be combined to eliminate d, the resistance of the yoke, and the resistance of X will be expressed by the resulting equation

$$X = \frac{A(A+B_1)}{B_1(A+B_2)} R$$

*This is essentially the scheme described by F. A. Laws in *Electrical Measurements*. Another method for the measurement of low resistance by means of a Wheatstone bridge is described by F. Wenner and A. Smith in *Scientific Papers of the Bureau of Standards*, No. 481.

PURPOSE OF THE KELVIN BRIDGE (Continued)

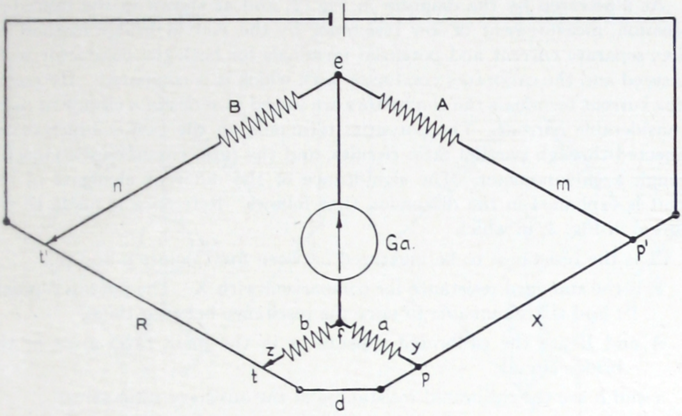


Fig. 2

The resistances R, X and d must be capable of carrying a considerable current without undue heating, because such a current is necessary for precision of balance. The yoke d must be of very low resistance, and must be firmly clamped to the rod and the standard so that contact resistances will be low and constant. The ratio arms A and B must be of such resistance that the resistance of the leads from them to the potential terminals p′ and t′, and the contact resistances at these points, will have no significant effect on the ratio of A to B.

The circuit shown in Fig. 1-b can be modified so that, at least theoretically, the effect of the yoke resistance is nullified and the resistance of X is determined by a single measurement. This is accomplished by the arrangement shown in Fig. 2, which is a diagram of the Kelvin bridge circuit. The yoke resistance is shunted by two resistances a and b in series, connected between the potential terminals p and t, and one galvanometer terminal is connected to the junction between these two resistances. Thus a and b constitute a second ratio circuit, and for this reason the device is sometimes called the Kelvin double bridge.

KELVIN BRIDGE THEORY

As illustrated by the diagram in Fig. 2, and as shown in the preceding discussion, measurement of low resistance by the Kelvin bridge method requires separate current and potential terminals for both the conductor to be measured and the calibrated conductor with which it is compared. By means of the current terminals the conductors are joined in series in a circuit to carry a considerable current. The potential terminals on the two conductors are connected through parallel ratio circuits, and the ratio circuits are connected through a galvanometer. The significance of the different elements of the circuit is explained in the discussion that follows. Reference is made to the diagram in Fig. 2, in which

X is the resistance to be measured between fixed points p and p′.

R is the standard resistance for comparison with X. The potential points t and t′ are movable to vary the resistance between them.

A and B are the calibrated resistances in the main ratio arms of the bridge circuit.

a and b are the calibrated resistances in the auxiliary ratio arms.

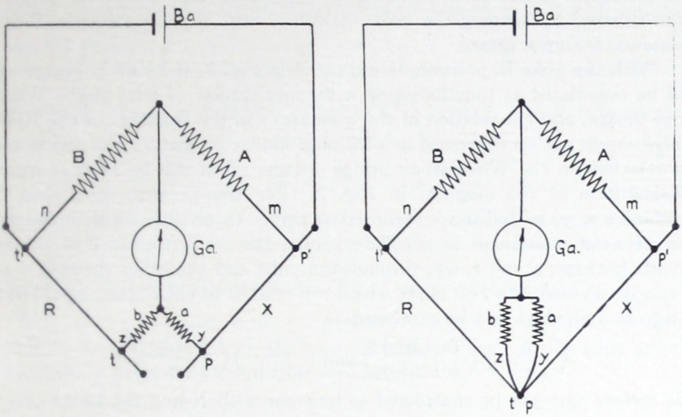
d is the connection, called the yoke, between one end of X and the adjacent end of R. The total yoke resistance actually includes that of the connecting link itself and that of the ends of the conductors between the yoke and the potential points p and t.

m, n, z and y are the resistances of leads and contacts in connections between the ratio arms and the two conductors.

With the circuit as shown in Fig. 2 most of the current flows between X and R through the yoke, but some of it flows through the ratio circuits. If the potential at e in one ratio circuit differs from that at f in the other ratio circuit, current will flow through the galvanometer between the circuits. If e and f are movable contacts on the respective ratio resistances, they can be adjusted to such positions that they will be at the same potential, and no current will flow through the galvanometer. With the contacts e and f fixed the potential points t and t′ can be adjusted until the potential is the same at e and f. In practice it is convenient to have e, f, t and t′ all adjustable, as described later.

When the elements of the circuit are adjusted so that no current flows in the galvanometer, the resistance X between the points p and p′ is related to the resistance R between the points t and t′ as the resistance A is related to the resistance B. For this condition, however, there must also be the same relation between the resistances a and b. It is not necessary that A = a and B = b, but only that $\frac{A}{B} = \frac{a}{b}$; but in practice it is generally preferable to have the two ratio circuits identical.

KELVIN BRIDGE THEORY (Continued)



Figs. 3a and 3b

The formula $\frac{X}{R}=\frac{A}{B}$ is that for the relation of the resistances in a balanced Wheatstone bridge circuit. These relations may exist in a Kelvin bridge circuit also, as can be illustrated by considering the Kelvin bridge circuit in conditions in which it is essentially the same as thcse of the Wheatstone bridge. Two such conditions, one possible and one hypothetical, are indicated in Figs. 3-a and 3-b. Each one assumes an extreme value for the resistance of the yoke, which may be regarded as infinite in Fig. 3-a and as zero in Fig. 3-b.

With the circuit shown in Fig. 3-a the resistance in one arm would be $X+y+a$ and in the other arm $R+z+b$. The resistance of X could not be determined with even approximate accuracy with the bridge in this condition. In some circumstances in the use of a Kelvin bridge for measurements of high precision this condition is purposely established by removing the yoke, so that certain preliminary adjustments of the ratio resistances can be made, but the yoke is replaced before actual measurement is made with the bridge. (See page 16.)

In the arrangement shown in Fig. 3-b it is assumed that the yoke resistance is reduced to zero by bringing the potential points p and t together. If this condition were possible, a, b, y and z would be simply extra resistance in series with the galvanometer, and therefore of little significance. Although

KELVIN BRIDGE THEORY (Continued)

this condition cannot be established in an actual bridge assembly, it can be approximated by keeping the yoke resistance low. The importance of yoke resistance is shown later.

With the yoke in position as indicated in Fig. 2, the Kelvin bridge may still be considered as functioning in a manner similar to that of the Wheatstone bridge, and the relation of the resistances in the branches of the Kelvin bridge circuit can be expressed in a formula similar to that for the corresponding relations in the Wheatstone bridge circuit. This will be evident from a consideration of the diagram in Fig. 2. For the present discussion, the resistances x, y, m and n are regarded as zero. In accordance with the relation between resistances in parallel circuits, the total resistance of the two circuits between p and t, one through the yoke and the other through a and b, can be divided into two parts which are related to each other as the ratio of a to b, and which can be expressed as

$$\left(\frac{a}{a+b}\right)\left(\frac{(a+b)\,d}{a+b+d}\right) \text{ and } \left(\frac{b}{a+b}\right)\left(\frac{(a+b)\,d}{a+b+d}\right)$$

The former part can be considered as in series with X and the latter part as in series with R, and the relation of the four arms of the bridge will be

$$\frac{X+\left(\frac{a}{a+b}\right)\frac{(a+b)\,d}{a+b+d}}{R+\left(\frac{b}{a+b}\right)\frac{(a+b)\,d}{a+b+d}}=\frac{A}{B}$$

When this equation is simplified, the expression becomes

$$\frac{X}{R}=\frac{A}{B}+\frac{d}{R}\left(\frac{b}{a+b+d}\right)\left(\frac{A}{B}-\frac{a}{b}\right)$$

This is the general formula for the relation of resistances in the Kelvin bridge circuit. If the resistances A, B, a and b are so adjusted that $\frac{A}{B}=\frac{a}{b}$ the last term in the above equation equals zero, and the formula becomes simply $\frac{X}{R}=\frac{A}{B}$.

In that condition the measurement of X is not affected by the resistance of the yoke. When the ratios $\frac{A}{B}$ and $\frac{a}{b}$ are not equal, the term $\frac{d}{R}\left(\frac{b}{a+b+d}\right)$ $\left(\frac{A}{B}-\frac{a}{b}\right)$ represents a correction factor, which may be considered in three parts, each of which should be made as small as possible.

If the ratios $\frac{A}{B}$ and $\frac{a}{b}$ are not equal, an equality can be established by shunting a or b, according to which is the higher resistance. If the yoke is removed, as in Fig. 3-a, the resulting Wheatstone bridge circuit will be in a

KELVIN BRIDGE THEORY (Continued)

balanced condition when the relation of the resistances is $\frac{A}{B}=\frac{X+a}{R+b}$ and this will be the relation if a resistance is connected in parallel with a or b and is adjusted until the galvanometer indicates a balance. When this condition is established $\frac{A}{B}$ will be very closely equal to $\frac{a}{b}$ because X and R will be very low resistances as compared with a and b, and will be in the relation $\frac{X}{R}=\frac{a}{b}$. Hence if $\frac{A}{B}=\frac{X+a}{R+b}$ it may be generally assumed that $\frac{A}{B}=\frac{a}{b}$ within very narrow limits. If the yoke is now replaced and the resistance standard R is adjusted until the galvanometer shows a balance, the resistance of X can be derived from the formula $\frac{X}{R}=\frac{A}{B}$ without correction.

If X and R are both fixed resistances, it might be expedient to shunt both A and a or B and b. In this case the two shunts must be kept strictly in the ratio of the resistances which they shunt.

If the resistance of the yoke could be made zero, as indicated in Fig. 3-b, the correction factor would be zero; but this is not practicable. It is generally practicable, however, to make d very low in resistance, so as to keep the fraction $\frac{d}{R}$ as small as possible. This is always important, as shown by the relation of this fraction to the correction factor. This fraction can always be made fairly small when R is 0.01 ohm or larger, but it is more difficult when R is smaller.

The raction $\frac{b}{a+b+d}$ cannot be materially altered, because a and b are governed by the relative values of X and R, and d is negligible in comparison with a+b. Because of the relatively small value of d, the fraction may be considered as equivalent to $\frac{b}{a+b}$. The numerical value of this fraction is always less than one; in fact it will be approximately as follows, according to the ratio $\frac{a}{b}$.

When $\frac{a}{b}=1, \frac{b}{a+b}=\frac{1}{2};$

$\frac{a}{b}=10, \frac{b}{a+b}=\frac{1}{11},$ say 0.1;

$\frac{a}{b}=1/10 \ \frac{b}{a+b}=10/11,$ say 1.0.

KELVIN BRIDGE THEORY (Continued)

The significance of these values is in the effect of the fraction $\frac{b}{a+b}$ in reducing errors due to the term $\left(\frac{A}{B}-\frac{a}{b}\right)$ in the correction factor. The numerical value of $\left(\frac{A}{B}-\frac{a}{b}\right)$ is determined below for three conditions, which will be sufficient for the present discussion. The results for these three conditions are based on the assumption that the ratio $\frac{A}{B}$ is 0.01 per cent higher than it should be, and the ratio $\frac{a}{b}$ is 0.01 per cent lower than it should be. With such errors the values for $\frac{A}{B}-\frac{a}{b}$ would be as follows:

For the nominal value $\frac{A}{B}=1, \quad \frac{A}{B}-\frac{a}{b}=0.0002;$

$\frac{A}{B}=10, \quad \frac{A}{B}-\frac{a}{b}=0.002;$

$\frac{A}{B}=0.1, \quad \frac{A}{B}-\frac{a}{b}=0.00002.$

The effect of such conditions will be more clearly demonstrated if d is considered as negligible in the fraction $\frac{b}{a+b+d}$ and the general equation for the Kelvin bridge, $\frac{X}{R}=\frac{A}{B}+\frac{d}{R}\left(\frac{b}{a+b+d}\right)\left(\frac{A}{B}-\frac{a}{b}\right)$ is simplified. The unknown resistance X in terms of the standard R is then expressed as

$$X=R\left[\frac{A}{B}+\frac{d}{R}\left(\frac{b}{a+b}\right)\left(\frac{A}{B}-\frac{a}{b}\right)\right]$$

If it is further assumed that $\frac{d}{R}=1$, the expression becomes

$$X=R\left[\frac{A}{B}+\frac{b}{a+b}\left(\frac{A}{B}-\frac{a}{b}\right)\right]$$

From the equation in this form it is apparent that the error due to $\frac{A}{B}-\frac{a}{b}$ is lessened by the factor $\frac{b}{a+b}$, and it is added directly to the error of the ratio $\frac{A}{B}$.

From the above considerations it appears that errors in A, B, a and b will result in maximum final errors of measurement as shown in the following

KELVIN BRIDGE THEORY (Continued)

table for three nominal values for $\frac{A}{B}$, if each ratio $\frac{A}{B}$ and $\frac{a}{b}$ is in error in such direction as to be cumulative.

Nominal Ratio $\frac{A}{B}$	$\frac{A}{B}$	$\frac{b}{a+b}$	$\frac{A}{B}-\frac{a}{b}$	$\frac{A}{B}+\frac{b}{a+b}\left(\frac{A}{B}-\frac{a}{b}\right)$	Error, Per Cent
1.0	1.0001	0.5	0.0002	1.0001 +0.0001	0.02
10.0	10.001	0.1	0.002	10.001 +0.0002	0.012
0.1	0.10001	1.0	0.00002	0.10001 +0.00002	0.03

Effect of Lead and Contact Resistances:

In the preceding discussion of the theory of the Kelvin bridge it was assumed, as stated on page 8, that the resistance of leads and contacts is zero, and that each of the letters A, B, a and b represents the total resistance of the ratio arm which it denotes. On consideration of the diagram of a bridge assembly in Fig. 4, it will be evident that the resistance of each arm in an actual bridge may include not only that of the ratio coils but also that of connections between the ratio arms and the resistances X and R. In Fig. 2 these extra resistances are indicated by the letters m, n, y and z. For strict accuracy the ratios should be expressed as $\frac{A+m}{B+n}$ and $\frac{a+y}{b+z}$. The formula for the relation of the resistances in the Kelvin bridge circuit at balance would then be $\frac{X}{R}=\frac{A+m}{B+n}$ and for this relation to be absolutely true, it would be necessary that $\frac{A+m}{B+n}=\frac{a+y}{b+z}$.

While the resistance of the ratio coils can be adjusted so that $\frac{A}{B}=\frac{a}{b}$ within very narrow limits, the equality may be less exact when the connecting wire resistances m, n, y and z are included. If the ratio coils were always of such resistance that $\frac{A}{B}=1$, it would be easy to make $\frac{A+m}{B+n}=\frac{a+y}{b+z}$ by adjustment of the resistance of the connecting wires so that $m=n$ and $y=z$; but for general use a Kelvin bridge is adapted for a variety of ratios other than $\frac{A}{B}=1$, and the resistance of the corresponding wires must be considered accordingly. For accurate results the adjustment is such that $\frac{A}{B}=\frac{m}{n}$ and $\frac{a}{b}=\frac{y}{z}$. The resist-

KELVIN BRIDGE THEORY (Continued)

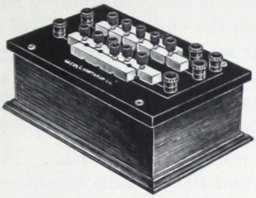
ance of the contacts at the ends of the connecting wires is disregarded in this consideration, because t can be made negligibly small in comparison with even the lowest ratio coil resistance.

As stated on page 6, it is not absolutely essential that A = a and B = b; it is only required that $\frac{A}{B}=\frac{a}{b}$. Then if $\frac{A}{B}=\frac{m}{n}$ and $\frac{a}{b}=\frac{y}{z}$, the expression $\frac{A+m}{B+n}=\frac{a+y}{b+z}$ will be equivalent to $\frac{A}{B}=\frac{a}{b}$. For practical purposes, however, in a Kelvin bridge circuit the corresponding coils in the two arms are usually alike, and the auxiliary ratio $\frac{a}{b}$ is adjusted with the same care as the main ratio $\frac{A}{B}$ so that the two are equal. It remains for the user to adjust the resistance of the external connections so that $\frac{A+m}{B+n}$ shall be as nearly equal to $\frac{a+y}{b+z}$ as can be made, when circumstances require it. Ordinarily it is sufficient to use connecting wire of ample size and low resistance without serious concern for the ratio of one lead to the other, if they are approximately alike; but when measurements must be made with great precision, the connecting wire resistances must be adjusted to the proper ratio.

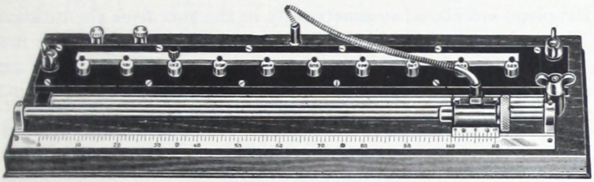
Kelvin Bridge Design and Operation:

The design of a Kelvin bridge must provide means for connecting a conductor of unknown resistance in series with a conductor of known resistance in a circuit that will carry a considerable current, and means for connecting potential terminals on one conductor with corresponding terminals on the other through two ratio arms by which the relation of the unknown to the known resistance can be determined. It must also provide means for adjusting either the standard resistance or the ratio arms to balance the bridge. If the resistance of the standard is fixed the ratios should be continuously adjustable, and if the resistances of the ratios are fixed, tha of the standard should be continuously adjustable. In an instrument for general use both the ratios and the standard resistance are adjustable. In a Kelvin bridge assembly the adjustable ratios and adjustable standard may be used as separate units, or they may be combined in a complete instrument. Both types of bridge are illustrated in the following pages.

STANDARD KELVIN BRIDGE



No. 4320 Set of 10 Ratio Coils



No. 4300 Adjustable Standard Low Resistance

Standard Kelvin Bridge:

With the two instruments illustrated above a Kelvin bridge can be assembled for measurement of resistance in the range from 0.000 000 01 ohm to 1 ohm in steps of scale divisions and ratio multipliers. Readings can be made to a precision of 0.04 per cent or better down to 0.000 025 ohm. The electrical circuits of these instruments are indicated in diagram in Fig. 4, showing how they are used in an assembly for measuring low resistance.

The standard resistance is adjustable at two points. Fine adjustment is made by moving a contact on a calibrated bar. The total resistance of the bar is 0.0011 ohm. In series with the bar are nine fixed resistances of 0.001 ohm, each of which can be added to the circuit by a plug and block connection. This is equivalent to having a graduated bar ten times as long as the actual bar, hence the precision of adjustment is ten times what it would be if the nine extra sections were not used. The scale of the bar has 100 divisions between 0 and 0.001 ohm, and a vernier provides means for reading to 0.1 division. The standard resistance required for balancing the bridge is therefore shown by the position of the plug and that of the vernier index. In calibrating the standard resistance each of the fixed coils is adjusted to its nominal value within a limit of error of 0.04 per cent. The limit of error in the bar resistance is 0.2 scale division.

STANDARD KELVIN BRIDGE (Continued)

The standard resistance is designed to carry 50 amperes for a period not exceeding 10 minutes when the entire resistance of the standard is in circuit. If only the bar is in circuit without the additional fixed resistance, it will carry 150 amperes for a short period. For continuous service the current in the entire bridge may be 30 amperes and that in the bar alone 90 amperes. There is a binding post on the bar which permits using it alone.

For the ratio arms a set of 10 coils is used. There are five coils, respectively 100, 300, 400, 1000 and 10,000 ohms resistance, for the two arms of the main ratio circuit, and five duplicate coils for the auxiliary ratio circuit. The coils are connected in the bridge circuit by plug and block connectors, the ratio values being determined by the position of the plugs in the blocks. When the plugs are placed symmetrically in the two arms the ratios are identical. The resistances included in the set provide the convenient multipliers of 100, 10, 1, 0.1 and 0.01, with several other ratios less commonly used. The resistance of each coil is adjusted to within 0.05 per cent of its nominal value, and for any combination the ratios $\frac{A}{B}$ and $\frac{a}{b}$ are equal within 0.01 per cent so far as the coils themselves are concerned.

The lowest ratio resistance is 100 ohms. If the lead and contact resistance in series with it were as much as 0.01 ohm, the error involved in this branch of the ratio would equal 0.01 per cent. It is possible, however, to keep the stray resistance below 0.01 ohm, so that the error will be less than 0.01 per cent for this ratio element. For the higher ratio resistances it will be proportionately still lower.

Measurement of Conductivity with the Standard Kelvin Bridge:

An important application of the Kelvin bridge is in determination of the conductivity, resistivity and temperature coefficient of samples of wire and rod. This requires measurement of resistance to an accuracy comparable with that obtained with the Standard Kelvin Bridge. An assembly in which such a Bridge is used for this purpose is represented in diagram in Fig. 4. The elements of the circuit are lettered in this diagram as they are in Fig. 2, so that the principles discussed in the preceding pages may be observed in their application in this assembly.

As in the previous illustrations, X represents the resistance to be measured between the potential points p and p′ on a low resistance conductor, which in this instance is a sample rod for conductivity determination. The sample is cut to a definite length, which should be known accurately within 0.05 per cent. The weight of the sample must also be determined to the same accuracy. The rod is then mounted in suitably devised clamps which provide two pairs of separate current and potential contacts. Shears, balances and

STANDARD KELVIN BRIDGE (Continued)

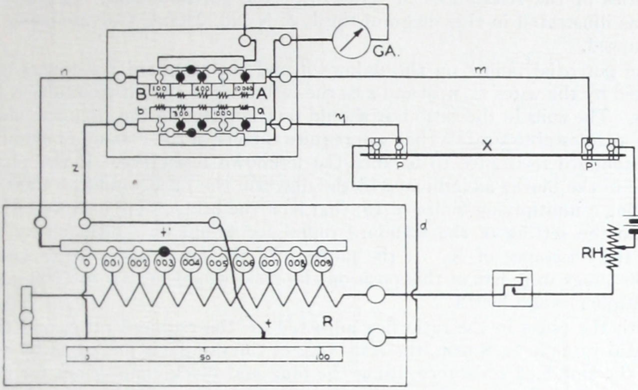


Fig. 4

clamps specially adapted for this service are described on page 19. The distance between the potential points must be measured accurately, for the resistance measured is that between these two points. One current terminal on the sample is connected by a heavy wire d to a binding post at one end of the calibrated rod in the standard resistance R. Since this wire comprises the yoke (see page 5) its resistance should be low. The other current terminals of the sample and the standard resistance are connected to the storage battery Ba through the rheostat Rh. There should also be a key in the battery circuit so that no current will flow when the key is open. This will help to avoid unnecessary heating in the circuit.

A rheostat is used to control the current in the bridge circuit according to the capacity of the unknown resistance to carry current without undue heating. While a piece of No. 000 copper wire will safely carry 50 to 100 amperes, a current of more than 20 amperes would heat a piece of No. 0 wire enough to change its resistance.

The current in the bridge circuit should be no larger than is required for a sufficient difference of potential at the terminals of the galvanometer (see e and f in Fig. 2) to indicate small differences in resistance in the unknown and the standard. Since the galvanometer is connected between the ratio arms there is always an appreciable resistance in series with it. The essential characteristic of a galvanometer for work with a Kelvin bridge is therefore a sensitivity to the current resulting from small differences of potential at the

STANDARD KELVIN BRIDGE (Continued)

extremities of the resistances in series with the galvanometer. For such a bridge as illustrated in this diagram the L & N No. 2500-C Galvanometer is well adapted.

The potential points on the unknown and the standard resistances are connected by the wires m, n, y and z to the terminals of the ratio circuits A-B, and a-b. The coils in the ratio box should be connected in the circuit in such manner as to establish ratios that will require the use of the maximum amount of the standard resistance to balance the unknown resistance. If the plugs were set in the blocks as indicated in the diagram the ratio would be 1000 to 100, giving a multiplying factor of 10; that is, if the bridge were balanced with this ratio the setting of the standard resistance would be multiplied by 10 to find the resistance of X. If the position of the box itself were reversed while the plugs were left in this position the ratio would be 100 to 1000, and the multiplier would be 0.1.

With the plugs in the ratio box adjusted for the required ratio, and the same ratio value in each arm, the resistance of the sample is measured by adjusting the standard resistance, using the plug and block connections for the major part of the resistance and the movable contact on the graduated bar for the final adjustment. The circuit is balanced when the galvanometer deflection ceases as the key in the battery circuit is closed and opened. The resistance of the sample between the potential contacts will then equal the setting of the standard resistance multiplied by the ratio value.

The temperature of the sample when the resistance is measured must be accurately determined. A wire or rod of pure metal has a considerable temperature coefficient of resistance, and in determining the conductivity of the sample a correction for temperature must be made to convert resistance at the measured temperature to resistance at the standard temperature (see page 17). For accurate determinations of conductivity the sample is commonly immersed in an oil bath when its resistance is measured, so that its temperature can be ascertained very precisely.

It is evident that in such an assembly the yoke resistance will probably be higher than that of the resistance measured, whereas in the discussion on page 8 it is explained that this resistance should always be low. When the yoke resistance is relatively high, it is essential that the ratio of a to b, including the lead resistance as well as the coil resistance, shall be correctly adjusted. To make this adjustment the yoke is disconnected after the bridge has been balanced as explained above. The circuit is then equivalent to that of a Wheatstone bridge (see page 7). The resistance of the wire y connecting the ratio element a to the potential point p is then adjusted until the galvanometer shows a balance for the bridge in this condition. Then the yoke is replaced to restore the conditions of the Kelvin bridge circuit, and the standard resistance is again adjusted for balance. In this case the effect of the yoke resistance will be negligible. This is in accordance with the discussion of corrections on page 8.

STANDARD KELVIN BRIDGE (Continued)

Formula for Computing Conductivity:

The conductivity of a sample of wire or rod is the reciprocal of its resistivity. Resistivity is specific resistance: that is, resistance per unit length and unit weight, or per unit length and unit cross section. To determine the conductivity of the sample when its length and weight or length and diameter are known, and its resistance for a given length has been determined at a known temperature, as explained previously, it is necessary to know the resistivity of the material of the sample. The temperature coefficient of resistance must also be known, because correction must be made if the resistance of the sample is measured at some other temperature than that for which the resistivity is stated.

If the sample is copper, according to the International Standard for Annealed Copper* the resistance of a piece of copper wire, of standard conductivity and uniform cross section, one meter long and weighing one gram is 0.15328 ohm at 20 deg. C., and the resistance of a piece of copper wire of standard conductivity one meter long and having a cross section of one square millimeter is 0.017241 ohm at 20 deg. C. These two values are in agreement when the density of copper is 8.89, but not at any other density. It is therefore important in stating the resistivity or conductivity of a sample to indicate which standard is used.

The conductivity of the sample on the basis of length and weight will be computed according to the formula given below, in which

L is the total length of the sample, reduced to meters;

d is the distance between the potential points, reduced to meters;

r is the resistance between the potential points;

w is the weight of the sample, in grams;

t is the temperature in degrees centigrade of the sample when the resistance is measured;

R is the resistivity at 20 deg. C. in ohm (meter, gram);

C is the conductivity in per cent of the above standard.

The resistivity of the sample can be expressed as

$$R = \frac{r\ w}{L\ d} + 0.0006\ (20^\circ - t)$$

where $0.0006\ (20^\circ - t)$ is the temperature correction for reducing resistance at the temperature of measurement to resistance at 20 deg. C. Since conductivity is the reciprocal of resistivity, the formula for per cent conductivity is

$$C = \frac{0.15328}{R} \times 100, \text{ therefore}$$

* Bureau of Standards, Circular No. 31.

STANDARD KELVIN BRIDGE (Continued)

$$C = \frac{0.15328}{\frac{r\ w}{L\ d} + 0.0006\ (20° - t)} \times 100$$

If L and w are measured in English units, they must be converted to metric units for use in the above equation. If t is measured in degrees Fahrenheit, it must be converted into degrees Centigrade. Application of the formula is illustrated in the following example:

The test sample is No. 9 B. & S. Gauge copper wire.

Length = L = 38 inches = 0.9652 meter.

Distance between potential points = d = 21 inches = 0.5334 meter.

Resistance between potential points = r = 0.001411 ohm at 22 deg. C.

Weight = w = 57.68 grams.

By substituting these numerical values for the corresponding symbols in the above formula,

$$C = \frac{0.15328}{\frac{0.001411 \times 57.68}{0.9652 \times 0.5334} + 0.0006\ (20 - 22)} \times 100; \text{ therefore}$$

C = 97.77 per cent of the (meter, gram) standard.

If the conductivity is desired in terms of length and cross section, the formula is as given below, in which

r is the resistance between potential points;

D is the diameter of the sample in millimeters (average of several measurements along the length of the sample);

d is the distance between potential points in meters;

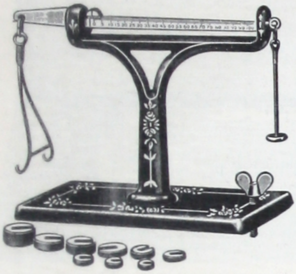
t is the temperature in degrees Centigrade of the sample when the resistance is measured.

$$C = \frac{0.017241}{\frac{r\ D^2 \pi}{d4} + 0.000068\ (20° - t)} \times 100$$

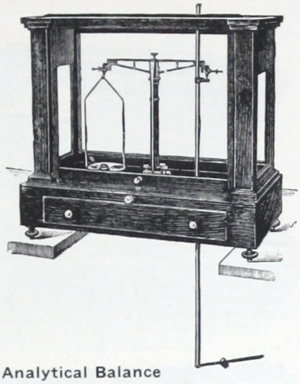
$$C = \frac{0.021952}{\frac{r\ D^2}{d} + 0.000086\ (20° - t)} \times 100$$

The importance of measurements such as those described above is evident from the fact that wire and rod for electrical conductors, and metals smelted and refined for their production, are commonly rated in commercial value according to their conductivity as compared with that of a standard. In plants where a large number of samples are measured each day, a conductivity bridge adapted for routine procedure, and requiring no calculations such as those described above, is more generally used. Such an instrument is the Hoopes Conductivity Bridge, described on page 20.

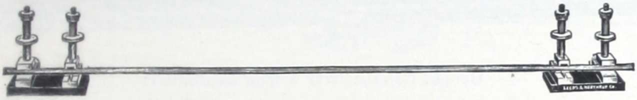
KELVIN BRIDGE ACCESSORIES



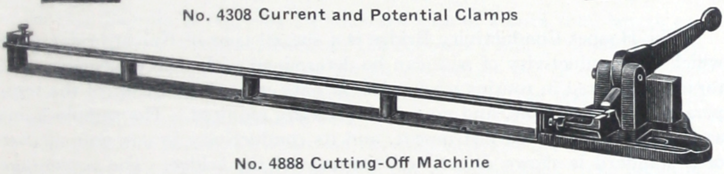
No. 4885 Yard Arm Scales



No. 4886 Analytical Balance



No. 4308 Current and Potential Clamps



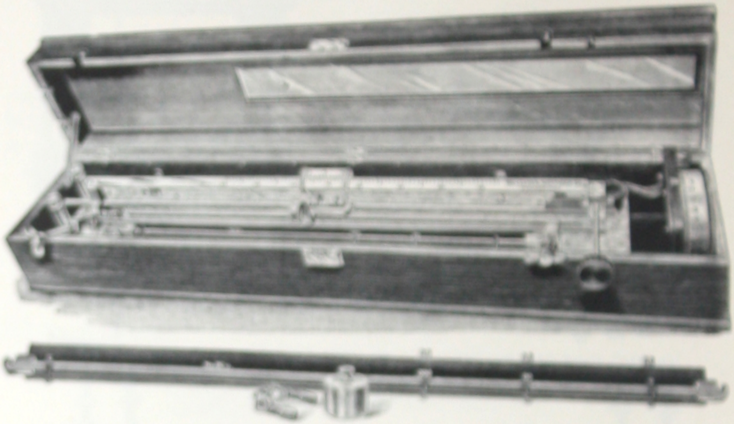
No. 4888 Cutting-Off Machine

With a Kelvin bridge equipment used regularly for measuring conductivity, specially designed clamps for making current and potential contacts with the sample of wire or rod are convenient. These are mounted in pairs, one current and one potential clamp attached to the same base comprising each unit of the pair. When the samples to be measured are always of the same length, the bases of the two units may be fastened to a common base to keep them always at the proper distance between potential points. When the clamps have been adjusted for a sample of a given diameter, a quick-acting spring contact device in each clamp permits insertion of other samples of approximately the same diameter without disturbing the adjustment of the clamp screws.

The special shear for cutting samples exactly to a given length is also a convenience for routine work in conductivity measurements.

A sample cannot be bent to put it in an ordinary balance for weighing. The scale or balance, arranged for weighing a sample of considerable length, is a necessary part of an equipment for conductivity work.

HOOPES CONDUCTIVITY BRIDGE



Hoopes Conductivity Bridge Equipment

The Hoopes Conductivity Bridge is a special type of Kelvin bridge with which the conductivity of wire can be determined with the convenience and rapidity required in routine work. No oil bath is needed to control the temperature of the sample, and no calculations are required. The sample is inserted in clamps in the instrument, and its conductivity in per cent of that of a standard is shown directly on the scale of the bridge. The percentage conductivity can be determined easily to a precision of better than 0.2 per cent.

In the Hoopes bridge the adjustable calibrated resistance of the usual Kelvin bridge is replaced by a fixed standard of the same material as that of the sample tested. A movable contact on the sample is adjusted to balance the bridge. The operation therefore consists essentially in finding the length of the sample wire that has the same resistance as that of a definite length of the standard wire; but since the conductivity of the standard is known the scale can be calibrated to show the conductivity of the sample in terms of that of the standard.

The circuit of the Hoopes Bridge is shown diagrammatically in Fig. 5. For convenience in comparison with the circuit of an ordinary Kelvin bridge, as shown in Fig. 2, corresponding elements are lettered similarly in the two diagrams.

HOOPES CONDUCTIVITY BRIDGE (Continued)

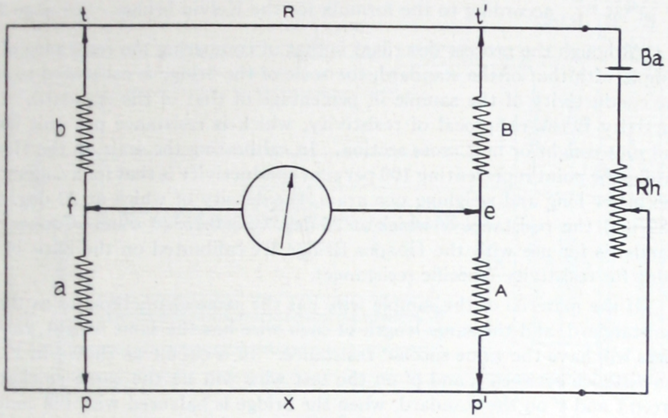


Fig. 5

In this diagram R represents a standard wire of known total length and weight, and known resistance between the contacts t and t′; while X represents a sample of wire also of known length and weight, but of unknown conductivity, which is to be determined by comparison of the resistance of the test wire with that of the standard wire.

The potential contacts t and t′ on the standard wire are fixed. The potential contact p on the test wire is fixed, but p′ is movable. The potential points p′ and t′ are connected through the main ratio circuit comprising two equal fixed resistances A and B, with a uniform slide wire resistance connecting their adjacent terminals. The potential contact e, at the terminal of one galvanometer connection, is movable on this slide wire. The auxiliary ratio circuit connecting the potential points p and t is identical with the main ratio circuit just described, and the other galvanometer terminal is adjustable at f on the slide wire in this circuit.

The contacts e and f are movable so that more or less of the slide wire resistance can be included in series with A and a, and correspondingly less or more in series with B and b, according to the direction in which the contacts are moved. This means for adjusting the ratio A to B and of a to b is used as a compensating device, as explained on page 23. For the present it is assumed that the contacts e and f are set so that A=a and B=b. If the bridge is balanced by adjusting the position of p′ until the galvanometer shows no deflection, the relation of the resistances in the bridge circuit will

HOOPES CONDUCTIVITY BRIDGE (Continued)

be $\frac{X}{R}=\frac{A}{B}=\frac{a}{b}$, according to the formula for the Kelvin bridge. See page 8.

Although the process described is that of comparing the resistance of the sample with that of the standard, the scale of the bridge is calibrated to show the conductivity of the sample in percentage of that of the standard. Conductivity is the reciprocal of resistivity, which is resistance per unit length and unit weight or unit cross section. In calibrating the scale on the Hoopes Bridge the point representing 100 per cent conductivity is that for a copper wire one meter long and weighing one gram, the density of which at 20 deg. C. is 8.89 and the resistance of which at 20 deg. C. is 0.15328 ohm. Copper wire standards for use with the Hoopes Bridge are calibrated on the basis of this value for resistivity (specific resistance).

If the material of the sample wire has the same characteristics as that of the standard, and the same length of each wire has the same weight, the two wires will have the same specific resistance. In a circuit as shown in Fig. 2, the distance between p and p′ on the test wire will be the same as that between t and t′ on the standard, when the bridge is balanced with the contacts e and f set so that the resistances in the ratio circuits are in the relation $A=B$ and $a=b$. In this case $\frac{X}{R}=\frac{A}{B}=\frac{a}{b}=1$, according to the formula on page 8. The position of the contact p′ will be that of 100 per cent conductivity on the scale.

If the sample wire and the standard wire are of the same material, but equal lengths of the two wires differ in weight, the actual resistance between the points p and p′ on the test wire will not be the same as that between t and t′ on the standard, even though the specific resistance is the same for both wires. The difference in weight indicates a difference in cross section, and the actual resistance varies with the cross section of the wire. If the contact p′ is left at the position of 100 per cent on the scale, which it should be because of the specific resistance of the wire, the bridge can be balanced by changing the ratio of A to B and of a to b. This is accomplished by moving the contacts e and f on the slide wire resistances between the ratio coils, as mentioned on page 21. The adjustment of the ratio thus compensates for the difference in weight per unit length of the sample.

If the ratio coils are left at this setting, and the same standard is kept in the bridge, but the sample is replaced by another having the same length and weight but differing in purity of the copper, it will be necessary to change the position of the contact p′ to balance the bridge, because the specific resistance of the less pure sample will differ from that of the standard. The position of p′ when the bridge is balanced will show the conductivity of the sample in terms of that of the standard.

HOOPES CONDUCTIVITY BRIDGE (Continued)

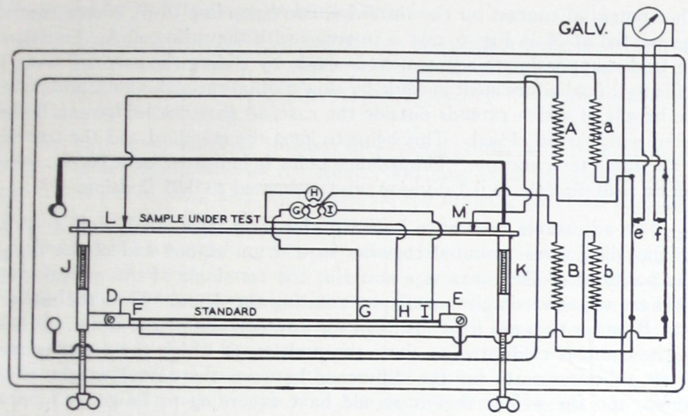


Fig. 6

The standard and the sample being both of copper, they will have so nearly the same temperature coefficient of resistance that when they are both at the same temperature during measurement, no correction for temperature is required in determining the conductivity of the sample.

Use of the Hoopes Bridge:

To show how the principles explained above are applied in an actual bridge, the diagram in Fig. 6 may be taken as a plan of the Hoopes Bridge and the standard wire illustrated on page 20.

The standard wire has a lug at each end, and is inserted in the bridge by fastening the lugs under set screws shown at D and E in Fig. 6. These are the current terminals of the standard. There are four potential contacts on the standard, at F, G, H and I, so that it can be used for comparison with test samples of three different gauge sizes. The contact at F is common to all three sections, and corresponds to the point t in Fig. 5. This contact is connected to one end of the ratio coil b. The contacts G, H and I are connected to three blocks so marked, and by inserting a plug in the proper block, one or the other of these potential terminals is put in series with the ratio coil B. The potential point selected will correspond with t′ in Fig. 5.

The ends of the test wire are inserted in the heavy screw clamps J and K, which provide current terminals for the wire. One potential terminal is at L, where the wire presses against a spring contact which is connected in series with the ratio coil a. This contact corresponds to the point p in Fig. 5. The

HOOPES CONDUCTIVITY BRIDGE (Continued)

other potential contact on the test wire, corresponding to p′, is on a carriage represented at M in Fig. 6, and is in series with the ratio coil A. To balance the bridge approximate adjustment is made by sliding the carriage along its guide rod; final adjustment is made by slow motion through a rack and pinion, the handle of which extends outside the case, so that the bridge can be balanced with the lid closed. This helps to keep the standard and the test wire at the same temperature. The balance point is indicated by a vernier which can be read directly to 0.1 division, and estimated to 0.05 division.

The adjustable resistance between the ratio coils A—B and a—b are circular slide wires mounted together in a drum at one end of the bridge. The positions of the contacts e and f at the terminals of the galvanometer leads are adjusted simultaneously by rotating the drum. Thus the ratios of A to B and a to b are kept identical for any position of the drum. A scale on the drum is calibrated to show the position at which the contacts must be set to compensate for the difference between the actual weight of the sample and the weight that it should have according to its gauge number. Such compensation is necessary because wire cannot be drawn exactly to a given size.

The proper setting for the scale of the drum is found by weighing the test sample in a special balance described on page 25. The sample is cut accurately to the required length and is suspended from one arm of the balance beam. In the pan on the other arm of the beam is a weight that will exactly counterpoise a wire of standard cross section for the gauge number of the sample. Any difference between the weight of the sample and the counterpoise is adjusted by moving a rider along the balance beam. The scale on the beam is calibrated to show, by the position of the rider, the per cent of excess or deficit in the weight of the sample in comparison with the standard or nominal weight of wire of that gauge number. The scale on the balance beam and the scale on the drum are alike, hence to compensate for the divergence in weight of the sample the scale of the drum is set according to the position of the rider when the sample is weighed.

Current for the bridge circuit is supplied by a storage battery of two volts connected to binding posts on the bridge. There should be a rheostat in the battery circuit to regulate the current according to the size of the wire tested, to avoid heating which will change the resistance of the wire. The maximum currents for different standard wire sizes are as follows:

No. 18.	About 3 amperes.	No. 6.	About 11 to 12 amperes.
No. 15.	About 4 amperes.	No. 3.	About 15 amperes.
No. 12.	About 4 to 5 amperes.	No. 0.	About 18 to 20 amperes.
No. 9.	About 8 to 10 amperes.	No. 000.	About 50 to 100 amperes.

HOOPES CONDUCTIVITY BRIDGE (Continued)

Accessories for Cutting and Weighing Samples:

The scale of the Bridge is calibrated in terms of the conductivity of a wire of given length and weight. A cutting-off machine and a balance, both specially calibrated, are therefore necessary for rapid, orderly cutting and weighing of samples to be tested.

The cutting-off machine consists of a metal frame with a shear at one end and an adjustable stop at the other. The stop is set to provide samples that are 38 inches long, plus 0.007 inch for the drawing effect on the end of the sample, caused by the shearing process.

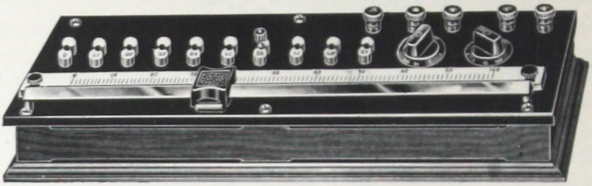
The balance for weighing samples resembles an ordinary laboratory balance, but is calibrated in terms of the settings on the Bridge. This direct-reading feature is most convenient because, if the weight of the sample differs from that of the standard, its conductivity will differ likewise and a compensating adjustment of the Bridge must be made. The value of this compensation is determined by balancing the sample against a counterpoise and a rider. The counterpoise weighs what the sample should weigh. If the two differ in weight, the operator slides the rider along the beam until a balance is secured. When this is done, the rider, pointing to the specially calibrated beam, indicates the proper setting for the compensator on the Bridge.

Each gauge size of wire requires its own counterpoise and rider, which are accordingly furnished with the standard. Since each standard may be adapted for checking three different gauge sizes of wire, the counterpoise and riders for all three sizes are sent with it. A counterpoise and a rider are shown beside the standard in the illustration on page 20.

The balance is equipped with devices for holding both thick and slender samples. A thick sample is held horizontally in a saddle, and a slender sample, that would bend under its own weight, is suspended vertically by means of a spring clip. Any sample of No. 21 B. & S. Gauge, or larger can be weighed with a limit of error within 0.1 per cent.

A special rheostat is very convenient for use with the Hoopes Bridge. The studs are marked to correspond with the standard wires, and when the lever is set on a given stud the current will be regulated properly for either of the three wires for which the corresponding standard is used. A plug can be inserted in the stud for the next larger standard to prevent moving the lever to a position for larger current. When the lever is set on the stud at one end of the row, no current will flow, hence the rheostat can be used as a switch also.

SELF-CONTAINED KELVIN BRIDGE



No. 4306 Self-Contained Kelvin Bridge

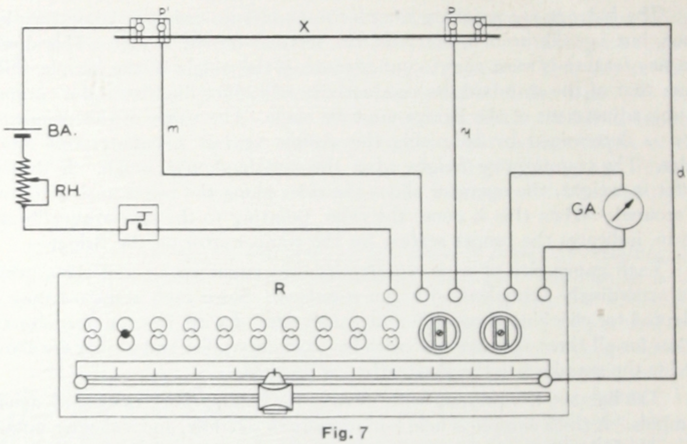
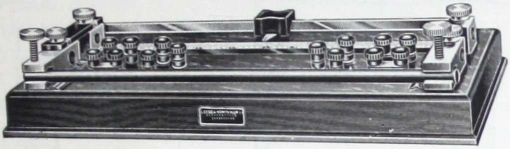


Fig. 7

A Kelvin bridge in which the standard resistance and the ratio circuits are incorporated in one instrument is illustrated above. Seven ratio values are provided, namely 0.1, 0.2, 0.5, 1, 2, 5 and 10. The limit of error in the calibration of the ratios is 0.05 per cent. The desired ratio is established in each ratio arm by setting a dial switch. The low resistance standard includes a graduated bar of 0.01 ohm resistance and 9 fixed resistors, each of 0.01 ohm, which can be put in series with the bar by a plug and block connector. The resistance of the bar and of each fixed resistor is accurate within 0.05 per cent of its nominal value. The scale for the bar has 100 divisions between 0 and 0.01 ohm. The limit of error in graduation of the scale is 0.2 division. The total range of resistance measurement in steps of scale divisions and ratio multipliers is from 0.000 01 ohm to 1 ohm. For resistance between 0.002 ohm and 1 ohm the limit of error in measurement with this bridge is 0.1 per cent. For lower resistances the accuracy is proportionately less.

STUDENTS' KELVIN BRIDGE



No. 4340 Students' Kelvin Bridge

This is a self-contained Kelvin bridge with which the principles of the Kelvin bridge method for measuring low resistance can be demonstrated. The standard of low resistance is a rod of uniform cross section and uniform resistance per unit length. The total resistance between potential terminals on the rod is 0.01 ohm within 0.5 per cent. One potential terminal on the rod is fixed; the other is a sliding contact by which the resistance can be varied continuously between 0 and 0.01 ohm. The position of the contact is indicated by a scale 15 inches (381 mm) long, having 100 uniform divisions.

The ratio arms comprise two identical sets of resistance coils connected to binding posts on the top of the instrument. The ratio desired is obtained by connecting the galvanometer terminals to appropriate binding posts. The ratio values available are 0.1, 1 and 10. The limit of error in the resistance of each ratio coil is 0.2 per cent, and the two ratios agree within this same limit.

The total range of resistance measurement with the bridge is 0.000 01 ohm to 0.1 ohm in steps of scale divisions and ratio multipliers. Resistance can be measured down to 0.001 ohm with a limit of error of 0.5 per cent. For the measurement of samples of wire or rod the sample is inserted in clamps on the instrument providing current and potential contacts. The length of sample required is about 18 inches. There are binding posts to which leads from other types of conductors than wire or rod can be attached. The yoke is removable so that a suitable yoke can be extended to conductors measured exterior to the bridge.

A feature of value in teaching is the means provided for inserting extra resistance in the ratio arms and the yoke, so that the effect of resistance in these elements of the circuit can be observed. These details are illustrated in Fig. 8, showing a schematic outline of the Students' Kelvin Bridge.

Corresponding elements are lettered the same in Fig. 8 as in Fig. 2. The external resistances m, n, y and z in series with the ratio coils represent links of sheet metal which in the actual bridge are connected between binding posts and are easily removable for replacement with higher resistance. The yoke d is a link of heavy metal and is also removable.

STUDENTS KELVIN BRIDGE (Continued)

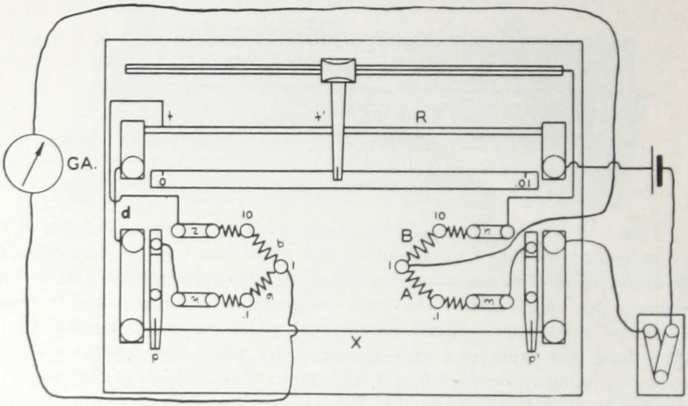


Fig. 8

Experiments with the Students Kelvin Bridge:

For the experiments here suggested the equipment needed will include with the Students' Kelvin Bridge a galvanometer of moderately high sensitivity, a dry cell and a key for the battery circuit. Connecting leads are furnished with the bridge. A piece of heavy copper wire with its resistance at one temperature certified is also furnished, and it can be used for preliminary experience in the operation of the equipment.

Clean the ends of the wire for good contact, insert them in the slots in blocks at the ends of the bridge, and clamp them tightly with the heavy thumb screws. The potential points on the wire are those at which the wire is in contact with metal strips beside the blocks.

Connect the dry cell and the key to each other and to the bridge as indicated in the diagram. A single dry cell connected through the leads furnished will supply ample current for the measurements to be made in these experiments. The current should be just sufficient to give the required sensitivity of action in the galvanometer. In any work with a Kelvin bridge, care must be taken to avoid errors from heating due to too much current in either the standard or the unknown resistance. When the current must be reduced, a rheostat can be connected in the battery circuit.

Since the precision with which the bridge can be balanced depends on the sensitivity of the galvanometer, the instrument used should have a sensitivity that will permit control of the current within the limit at which undue heating will occur. Connect the terminals of leads from the galvanometer to binding

STUDENTS' KELVIN BRIDGE (Continued)

posts in the ratio circuits, using posts numbered alike for both terminals. Always use the ratio that will bring the movable contact as high as possible on the calibrated resistance for balance in measuring an unknown resistance. Use the post marked 0.1 for resistance below 0.001 ohm, the post marked 10 for resistance above 0.01 ohm and the post marked 1 for resistance between these limits. The resistance of the copper rod furnished with the bridge is usually a little more than 0.000 05 ohm. This would require the 0.1 ratios, and the sliding contact would be just over half way along the calibrated standard

Close the battery key and move the sliding contact along the standard resistance until the bridge is balanced. The balance point is determined when the galvanometer deflection ceases as the key is opened or closed. The index may not be exactly at zero when the bridge is balanced, because there may be thermo-electric forces due to unequal temperatures of junctions of different metals in the circuit, and they may cause a slight deflection of the galvanometer even when the key is open. The position of the index resulting from the effect of these forces will be the zero position in the resistance measurement. This condition has no effect on the accuracy of measurement.

The resistance of the sample measured is derived from the formula $X = \frac{A}{B} R$, in which X is the unknown resistance, R is the reading of the scale on the standard resistance when the bridge is balanced, and $\frac{A}{B}$ is the ratio multiplier, the numerical value of which is shown at the base of the binding posts to which the galvanometer leads are attached.

Compare the resistance of the copper rod measured according to the above directions with its known resistance. If there is a discrepancy, it may be due to a difference in temperature of the sample at the two measurements, or it may be due to poor contacts in the circuit. Note whether the contact surfaces of the rod, the yoke and the links are clean, and clamp the thumb screws and binding posts tightly. Then repeat the measurements.

Find the temperature of the sample by means of a reliable thermometer close to it, and compare it with the temperature at which the known resistance of the sample was determined. The temperature coefficient of resistance of copper is approximately 0.4 per cent per degree C.

Find the weight of the copper rod, its total length and the distance between the potential points, and determine the conductivity of the sample by means of the formula on page 18.

Effect of Stray Resistance in the Bridge Circuit:

For these experiments the following accessories will be needed:

Three rods the same length as the copper rod but of different diameters with respective resistances of the order of 0.08, 0.008, and 0.0008 ohm. These

STUDENTS' KELVIN BRIDGE (Continued)

will provide for the use of all three ratio values while requiring in each case the major portion of the standard resistance to balance the bridge. Some material with higher specific resistance than that of copper and with negligible temperature coefficient is preferable. An alloy of copper, nickel and manganese is satisfactory and the diameters of rods of suitable alloy for the resistances suggested would be approximately 4, 7 and 10 mm.

Four resistance coils of 10 ohms each, and 4 coils of 1 ohm each.

Two yokes of different diameter, both smaller and appreciably higher in resistance than the one in the bridge.

Lead and Contact Resistances:

a. With the bridge in its normal condition as used in measuring the copper rod, measure and record the resistance of each of the test rods, using the ratio setting that requires the maximum length of the standard resistance for balance. The results obtained in these measurements will serve as standards for comparison in the tests that follow.

b. Insert a 10-ohm coil in place of each of the links m, n, x and y and balance the bridge for each rod. Compare the results with those obtained in a and find the percentage of error.

c. Replace the 10-ohm coils with the 1-ohm coils and repeat the operation in the preceding paragraph.

d. Leave the 1-ohm coils at m and x. Put 10-ohm coils in place of those at n and y, and repeat the operation in b.

e. Reverse the positions of the coils and try other combinations, comparing the results in each case with those for the bridge in the normal condition.

Compare the results when the ratio of the external resistances is the same as that of the fixed resistances in the ratio circuit with the results when the external resistances have some other ratio.

Yoke Resistance:

a. Restore the bridge to its normal condition with the links at m, n, x and y, and record the position of the sliding contact on R to balance each of the three rods when using the yoke furnished with the bridge and when this yoke is replaced by each of the two yokes of higher resistance.

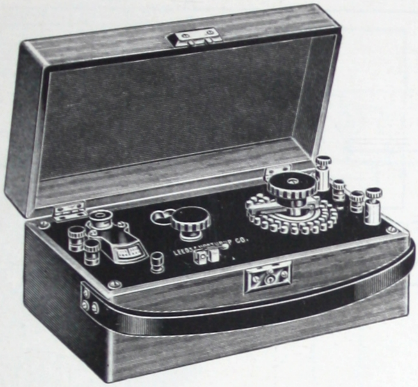
b. Insert the rod of lowest resistance in the bridge and replace the links at x and y with 10-ohm coils, leaving the links at m and n in place. Record the position of the sliding contact on R and balance with each of the three yokes.

c. With links at x and y and 10-ohm coils at m and n, record the measurement of the rods with all three of the links.

d. With 1-ohm coils at x and m and 10-ohm coils at y and n, record the measurements of the rod with all three yokes.

Compare the results obtained in these measurements with results obtained when the bridge is in its normal condition, and consider them in connection with the correction factor discussed on page 8.

PORTABLE KELVIN BRIDGES



No. 4285 Portable Kelvin Bridge

No. 4285 Kelvin Bridge:

A portable Kelvin bridge is a convenient instrument for measuring low resistance windings in generators and transformers. The instrument shown in the above illustration has a total range of 0.001 ohm to 25 ohms, which is sufficient for all ordinary applications of this nature. The elements of the circuit in this bridge are shown in diagram in Fig. 9.

An important application of measurements with this bridge is in determinations of the temperature of low resistance conductors, as for example in the cooling of transformer and generator windings temporarily discontinued from service. The accuracy of resistance measurement corresponds to a temperature accuracy of better than 1 degree C.

Operation:

The operation of this bridge differs somewhat from that of bridges previously described. A fixed amount of standard resistance is set in one branch of the bridge, and the circuit is balanced by adjusting the ratios (see page 12). A slide wire resistance is connected between the ratio coils A and B, and another between a and b. Both slide wires are mounted on the edge of a disc, and are moved together by the knob which rotates the disc. The contacts between the terminals of the galvanometer leads and the slide wires are set identically with relation to the two resistances, so that for any position of the disc, the ratio of A to B is the same as that of a to b.

The standard resistance comprises a series of calibrated low resistances connected to studs on a dial switch, so that the amount of resistance used for

PORTABLE KELVIN BRIDGES (Continued)

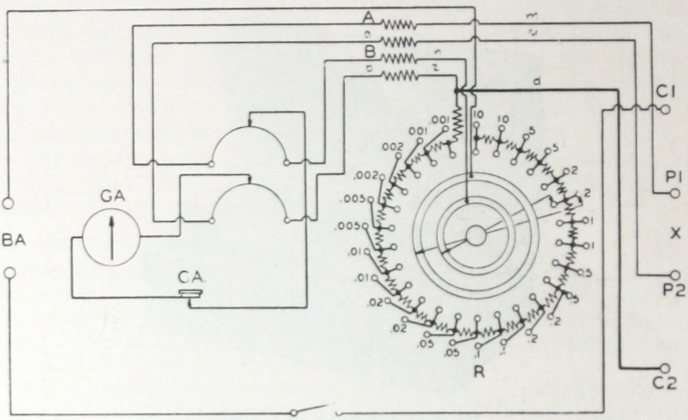


Fig. 9

comparison can be varied in fixed steps. The studs represent the current and potential contacts at one end of the comparison resistance.

To use the bridge a battery is connected to the binding posts BA, and leads from current and potential terminals of the resistance to be measured are connected respectively to posts C1, C2 and P1, P2. The dial switch is turned to set the brushes on the studs corresponding to the standard resistance nearest to the resistance measured. The battery switch is then closed, and the resistance between the ratio coils is adjusted by turning the slide wire until the galvanometer pointer does not move as the key GA is pressed and released. Unless the resistance to be measured is known approximately, the proper setting of the dial switch must be found by trial. When the bridge is balanced, the resistance measured is equal to the setting of the dial switch multiplied by the reading of the ratio scale.

No. 4286 Kelvin Bridge:

The illustration on page 33 shows a portable Kelvin bridge suitable for shop and laboratory work of moderate accuracy in measurement of low resistance in windings of motors, generators and transformers, and in wires, rods, bars, and carbon brushes. The range is from 0.0001 ohm to 11 ohms. The limit of error is within 2 per cent.

PORTABLE KELVIN BRIDGES (Continued)

No. 4286 Portable Kelvin Bridge

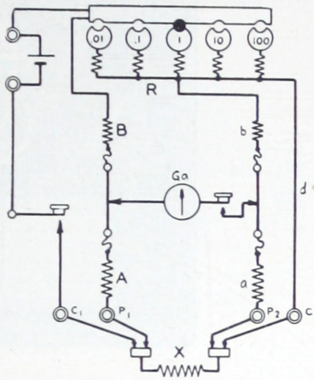


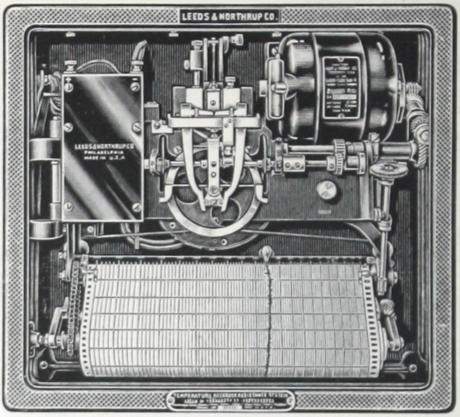
Fig. 10

Operation:

A diagram of the bridge circuit is shown in Fig. 10. The principle is that of comparing the unknown resistance with a fixed resistance by means of adjustable ratios. (See page 12.) The instrument has five fixed resistances, of 0.01, 0.1, 1, 10 and 100 ohms, any one of which can be used for comparison by inserting a plug at a block numbered correspondingly. The ratio resistances are a pair of slide wires mounted on the edge of a disc and rotated together by a knob. The operation consists merely in pressing a key and rotating the disc until the galvanometer shows a balanced circuit. The plug is set at the fixed standard which causes a balance as near as possible to the center of the ratio scale. The resistance measured is equal to the reading of the ratio scale multiplied by the numerical value of the standard resistance used. The computation amounts simply to shifting the decimal point in the scale reading.

When the resistance to be measured does not exceed 1 ohm, it must have current and potential terminals to be connected respectively to the posts C1, C2, and P1, P2. When the resistance is above 1 ohm, or at least is large in comparison with the total resistance of the connecting wires, one wire from each terminal will be sufficient. In connecting them to the bridge the end of one wire should be attached to both posts P1 and C1, and the end of the other wire to P2 and C2.

KELVIN BRIDGE TEMPERATURE RECORDER

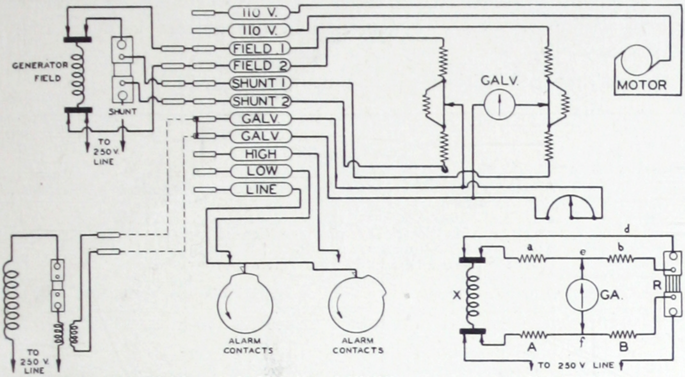


No. 8501 Kelvin Bridge Temperature Recorder For Generator Rotating Fields:

The instrument illustrated above records the temperature of the rotating field of a generator. The quantity actually measured is the resistance of the field, but since this changes with temperature the Recorder is calibrated in degrees.

The actual circuit of the bridge in this recorder is shown schematically in Fig. 11, accompanied by a simplified diagram, so that the elements of the circuit can be compared with those of the Kelvin bridge represented by Fig. 2 on page 6. The unknown resistance X is the rotor winding, and the standard resistance R is a low resistance shunt connected in series with the winding by the yoke d. The potential points p and p′ are auxiliary brush contacts on the collector rings, while t and t′ are fixed potential points on the standard resistance R. The bridge circuit is of the type in which differences between the unknown and the standard resistances are balanced by adjustment of the ratios (see pages 12 and 31). The terminals e and f of the galvanometer leads are movable contacts on slide wire resistances between the ratio coils A—B and a—b. As the resistance of X varies with temperature, the bridge circuit is balanced by adjusting the positions of these contacts on the slide wires, thus varying the ratio A to B and of a to b. This adjustment is made automatically by the recorder mechanism, which draws a curve showing the changes in ratio required to keep the bridge balanced. The scale is calibrated so that the record of the ratio adjustments indicates the corresponding temperatures of the field winding.

KELVIN BRIDGE TEMPERATURE RECORDER (Continued)



SCHEMATIC DIAGRAM OF DEVICE FOR NULLIFYING THE EFFECT OF INDUCTANCE IN FIELD WINDING

SCHEMATIC DIAGRAM OF RECORDER CONNECTIONS TO GENERATOR

SCHEMATIC DIAGRAM OF KELVIN BRIDGE

Fig. 11

Since the standard resistance can be mounted close to the generator, the resistance of the yoke d can be made very low, to satisfy this requirement of the Kelvin bridge circuit. (See page 8.) The ratio resistances A, B, a and b, with the slide wires between them, are mounted in the recorder, and since this may be at a considerable distance from the generator, there may be an appreciable amount of resistance in the leads m, n, y and z connecting the ratio coils with the current and potential points on the standard resistance and the field winding. By using wire of sufficient size and making good contacts, this resistance can be kept so low that being in series with ratio coils of comparatively high resistance, it will be an insignificant fraction of the total. Furthermore, the resistances can be adjusted so that any differences in them will have no important influence on the ratio of A to B and of a to b. (See page 12.)

Canceling the Effect of Change In Field Current

Because of self inductance in the winding a sudden change in field current may disturb the potential equilibrium at certain points in the bridge circuit. This may cause a deflection of the galvanometer and a change in the temperature record, although there has been no change in the actual temperature of the winding.

This effect is eliminated by connecting the galvanometer to the secondary of a current transformer, the primary of which is in series with the standard resistance and the field winding. A sudden change in current will thus produce a compensating e. m. f. in the galvanometer circuit and the temperature record will not be affected.

This refinement is only necessary when measuring the temperature of generators supplying a fluctuating load.

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